

High concentration linear Fresnel reflectors

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ABSTRACT

The late exponential development of Concentrating Solar Power (CSP) technology has driven to a very high power installed worldwide, but with no time for global optimization of the technology. High feed-in-tariffs have concentrated investments on trough collectors and central towers, previously studied during the 1980s. Linear Fresnel reflectors (LFRs) are regarded as a low efficiency technology, which is mainly due to very little previous research. However, the use of slightly bent mirrors drives to high concentration ratios, with obvious cost advantages over other CSP technologies. This paper studies the radiation flux obtained in a flat receiver using different mirror shapes, and analyzes its variation along the year. Linear Fresnel reflector design variables are reviewed, and a Ray Tracing model of the Fredemo prototype is carried out. Results show higher performances than expected.

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1. Introduction: the development of concentrating solar power

Concentrating Solar Power (CSP) development may be classified in three periods. During the late 1970s and 1980s a great hope was held on CSP as a possible technology to face energy dependence, mainly due to the 1973 and 1979 oil crises. This period drove to a vast scientific work on different ways of producing electricity from direct solar radiation [1–9]. During the first part of this period, research centered around central tower [10–15], parabolic trough [16–23] and parabolic dish [24–27]. This resulted in the construction of Solar One – focused on central tower technology – which operated successfully from 1982 to 1988 [28]; the inauguration of the Plataforma Solar de Almería in 1981, aimed at multiple CSP technologies, but focused on central tower at the beginning [29]; the achievement of the solar to electricity conversion efficiency record via the Vanguard Dish Stirling module in 1984 [27,30]; and the construction of Solar Energy Generating System (SEGS) during the 1980s, which ended with the installation 354 MW with trough technology, most of them in use nowadays [31].

Linear Fresnel reflectors had a late development compared to the other technologies: even though a few papers and patents on Fresnel lens, enhanced flat collectors and compound systems were published in the mid 1970s [33–36], there is no well-known published work until the second half of the 1980s [4,6–8,37–41], when oil prices reached minimum values. After energy crises, interest in CSP technologies was diluted, and therefore, neither LFR prototypes nor commercial plants were built during this period, researchers being less active in this domain [42–44].

Global Warming, afterwards called Climate Change, became a major issue at the end of the 1990s, the Kyoto Protocol (1997) being the paradigm of its importance. As a result, Spain played a major role in the development of CSP thanks to the Royal Decrees RD 436/2004 and RD 661/2007 [45], which established very high feed-in tariffs to promote these technologies. Such tariffs were high enough to make trough collectors technology with synthetic oils as heat transfer fluid (SEGS technology) profitable enough and, as no limit was set on total power installed, many identical solar power plants were projected and installed during the second half of the 2000s. Research, development and innovation were not such important matters as construction capabilities, the objective set by the companies being materials cost reduction. The increase in trough technology power installed may be observed in Fig. 1; whereas only three power plants were installed with central tower technology in that period (PS10 – 2007 – and PS20 – 2009 – with Direct Steam Generation, and Gemasolar – 2011 – with molten salts), with a total power installed of 50 MW; one 1.4 MW linear Fresnel power plant – 2008 – which is being upgraded now to 30 MW; and one 1 MW dish/engine solar field – 2010 – [32]. The non-equilibrated development of CSP in Spain is depicted in Fig. 2.

It is obvious that such a fast development on trough collectors – more than 1 GW installed during five years – implies an important advance in the CSP learning curve; however, this advance has only been made in the construction procedures and materials to reduce costs, as well as on thermal storage, lacking a previous overall research which would have laid down the possible ways to reduce costs in a lower level optimization. The industry has advanced in the learning curve, but we may ask if the advance has been done in the correct learning curve. At the beginning of 2012 the Spanish Government established a moratorium to the feed-in tariff; during such moratorium, no new renewable energy projects will be

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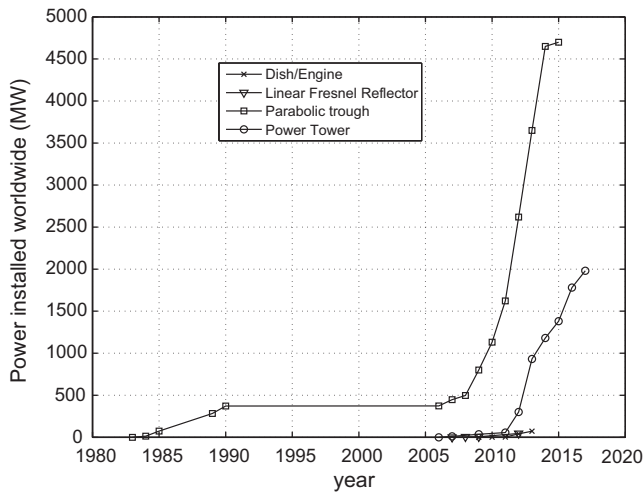


Fig. 1. Power installed worldwide since 1980 depending on the solar field technology (data from [31] and [32], January 2012).

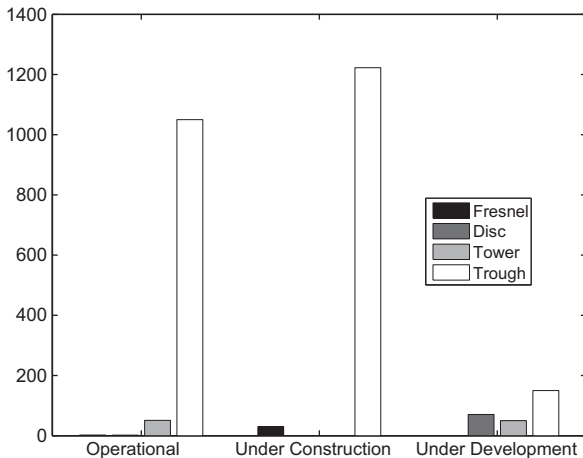


Fig. 2. Power (MW) of operational, in construction and in development CSP plants in Spain (data from [32], January 2012).

accepted, but those already approved will continue their construction. This can be considered as the end of the second period on the development of CSP.

The USA play the major role in the third period of the development of CSP, as happened in the first one. It can be said that this period started just after the explosion of the second period in Spain. Climate Change, but especially Energy dependence, became major issues for the US Government, and thus the Department of Energy decided to provide loan guarantees to Spanish and American companies to build CSP plants in the country, in addition to provide funds for research on such technology. One can observe in Fig. 3 that there is an equilibrium among trough collectors and central towers, the former being mainly built by Spanish companies, and the latter by Americans; this reveals that USA are willing to have their own technology, similar to Gemasolar (Central Tower with molten salts), while Spanish companies have made profit of the advance in the learning curve to export their technology.

Dish/Stirling still maintains the sun to electricity conversion efficiency record, which has resulted in numerous research projects on this technology, and a few commercial projects around the world. However, their modularity has ended to be a drawback instead of an advantage, as economies of scale cost reductions are

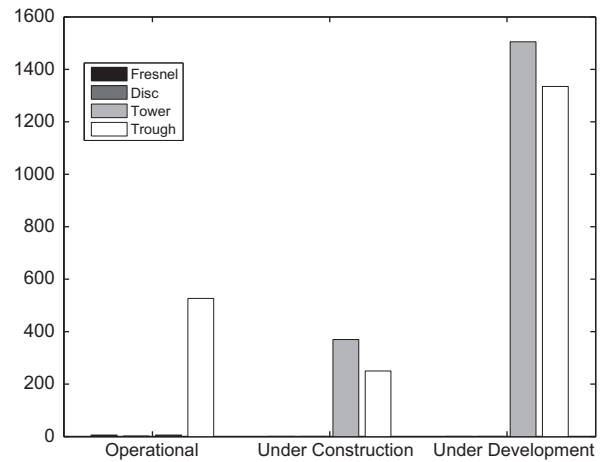


Fig. 3. Power (MW) of operational, in construction and in development CSP plants in the USA (data from [31], January 2012).

limited, and photovoltaic technology has been a competitor for the same area that has greatly reduced its cost.

On the contrary, it appears that linear Fresnel reflectors development has always occurred late: when scientific research started during the late 1980s, interest on CSP became lower due to oil prices diminution, and when LFR was installed in Spain, being nearly competitive with trough technologies, the economical situation resulted in a moratorium to renewable energies. Meanwhile, trough collectors have reduced costs by economies of scale thanks to an unsustainable growth, enlarging the gap with LFR. Even though investment on technologies is more equilibrated now thanks to the push of central tower, CSP industry should have a look backwards, and analyze whether the advance is being done in the correct learning curve.

At current time we have powerful tools that enable us to predict the potential of each technology; there is a general belief that LFR obtain very low concentration factors, but it is rare to find scientific work where the actual achievable concentration is analyzed. This paper intends to go towards this direction, find out advantages and disadvantages of LFR, and determine their potential for cost reductions. Section 2 is devoted to the analysis of the design variables in linear Fresnel reflectors, reviewing works already done. In Section 3 the concentration achieved for different mirror shapes and different days of the year is depicted, and values are compared to state of the art trough collectors results. Section 4 shows the advantage of reducing the filling factor in LFR. Finally, conclusions and future work are discussed in last Section, remarking the potential for cost reductions of this technology.

2. Solar field configuration: the design variables

2.1. Innovative receivers for linear Fresnel reflectors

The LFR receiver technology used has a major impact on the solar power plant, and will influence the optical design of the solar field. Reviewing the main companies that develop LFR technology – Novatec Solar [46], Areva Solar [47], Solar Power Group [48] and Industrial Solar [49] – it seems that all agree in the use of cavity receivers. This trend is also observed in the scientific works published, which have deeply studied such receivers [50–56].

Trapezoidal cavity receivers are suitable for solar applications because hot air is mainly found near the top surface of the cavity [54], which can be properly insulated. In addition, there is no direct radiation heat loss to the sky, as tubes are facing to the ground – obviously there is indirect radiation via the mirrors, but the ratio

between the solid angle to the sky and the one to the ground and receiver surfaces is very small compared to trough collectors. The drawback of these receivers is that, due to the width of the flat window, they cannot be evacuated, which implies first a convection component in heat transfer from the tubes to the window, and second the impossibility to use selective coating on the tubes if air (oxygen) is in contact with it. The latter problem is solved by [57], that suggests the use of pressure compensated nitrogen.

Even though most scientific work on LFR admit the use of cavity receivers [50–56,58–68], there are a few papers that assume the use of tubes without cavity [69,70]. However, besides Mills suggesting no cavity in 2000 [69], during his review in 2004 he talks about enhanced performance using trapezoidal cavity receivers [59]. Therefore it can be concluded that the use of trapezoidal cavity receivers such as the one shown in Fig. 4 is an important advantage of LFR technology when compared to trough collectors.

Nevertheless, there are still some important decisions to take in the design of the receiver, such as the use of one large tube or many thinner tubes (multitube receiver). The prototype built in Plataforma Solar de Almerfa (PSA) by DLR and Solarmundo – later called Solar Power Group – [48] uses a one tube receiver, with a secondary reflector above it and a window below. Similarly, Novatec Solar, another Germany company, has used such technology for commercial power plants PE1 and PE2 in Spain [46]. On the other side, Ausra – later bought by Areva Solar – built in 2008 the Kimberlina power plant in California, with open air multitube receiver [47].

This contrasts with scientific works published during recent years, which show a trend towards multitube receivers. In 2010 Singh published that multitube receivers would achieve higher efficiencies versus a rectangular tube occupying the same cross section [50,51], and papers studying heat transfer in trapezoidal cavity receivers after that always assumed a multitube receiver [52,54,55]. Finally, [56] carried out a comprehensive study on the influence of the tubes diameter on the heat transfer, and thus on the receiver's thermal efficiency.

It was proven that the exergetic efficiency of a Fresnel receiver is maximized for a given tube diameter, which depends on the radiation flux impinging onto the receiver, the heat transfer fluid and its inlet temperature, and the receiver's length. Fig. 5 shows the maximum exergetic efficiency achieved in a 300 m receiver, with an impinging radiation of only 8.3 kW/m² – implies a concentration ratio around 10 suns – and the synthetic oil Therminol VP-1 entering at 200 °C, for different tube diameters.

For radiation intensities of 16.6 kW/m² the exergetic efficiency increases up to 39%, while for 25 kW/m² it only achieves 43% [56]. Therefore, it is worthless to increase the concentration as much as possible; instead we should find the saturation area in exergetic efficiency. Such variable takes into account not only the outlet temperature, but also the pumping losses, as shown in Eq. (1). Assuming a multitube receiver such as the one depicted in Fig. 4, if the width is set fixed, a diminution of the tubes diameter

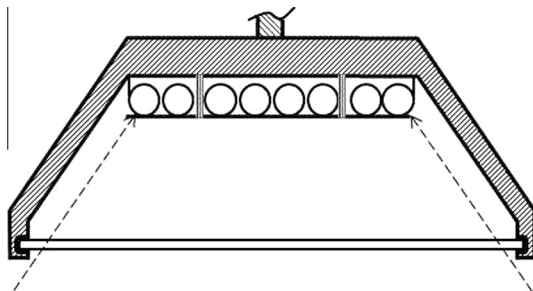


Fig. 4. Cross section of a multitube linear Fresnel receiver [57].

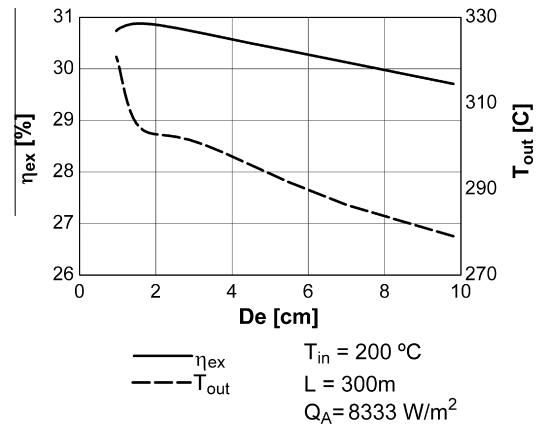


Fig. 5. Maximum exergetic efficiency and corresponding outlet temperature depending on the tubes diameter for a 300 m receiver with 8.33 kW/m² impinging radiation when the inlet temperature is 200 °C [56].

implies a smaller cross section, and therefore higher fluid speed for the same mass flow. In addition, it can be proven that the convection heat transfer coefficient for the fluid flowing within the tubes is proportional to the mass flow, and inversely proportional to the tubes diameter (for a given receiver's width), while the pumping power required is proportional to the cubic power of $\dot{m}/D$ [56].

$$\eta_{ex} = \frac{\dot{Q}_{gain} \cdot \left(1 - \frac{T_{env}}{T_{out}}\right) - \dot{W}_p / \eta_{th-el}}{\dot{Q}_{sun} \cdot \left(1 - \frac{T_{env}}{T_{sun}}\right)} \quad (1)$$

Thus, making tubes narrower drives first to a more efficient heat transfer, and so to an increase of the exergetic efficiency. However, when they become too small in diameter, pumping power becomes critical, and the efficiency attains a maximum. One may observe that diminishing even more the tube diameter reduces the exergetic efficiency by a significant increase of the outlet temperature. This is due to a reduction of the mass flow that intends to limit the pumping power, with a drawback of higher temperatures and thus lower thermal efficiencies.

It can be concluded that multitube cavity receivers, with no secondary reflector, seem to be more adequate for linear Fresnel reflectors. They have the advantage versus through receivers to minimize losses to the ambient via radiation to the sky, and the advantage when compared to Fresnel one-tube receivers to have a better heat transfer coefficient thanks to higher fluid speeds. In addition, the HTF may be preheated within the lateral strips, and heated to the final temperature in the central strip, thus maximizing the exergetic efficiency [71].

The number of receivers per mirrors array, and their location and orientation, vary among researchers. Prototypes and commercial plants built until current time consist of independent sets of arrays of mirrors with their own receiver in the middle line of the solar field, which is the option chosen by most authors. When this configuration is used, receivers are pointing horizontally to the ground. Alternatively, [69] suggest the use of multiple receivers, and alternate at some point mirrors that focus onto the receiver at one side, and mirrors that focus to the other side. Doing so, mirrors can be placed closer to each other without increasing shadowing and blocking effects, which is called Compact linear Fresnel reflectors (CLFRs). After [59], receivers would be oriented horizontally to the ground, as in the previous configuration. Finally, Martínez-Val et al. [72] suggest the use of independent arrays of mirrors, each of them having a linear tower in the middle where two receivers are placed orienting to one side each. This configuration allows lower impinging angles for far mirrors, and so the arrays can be wider;

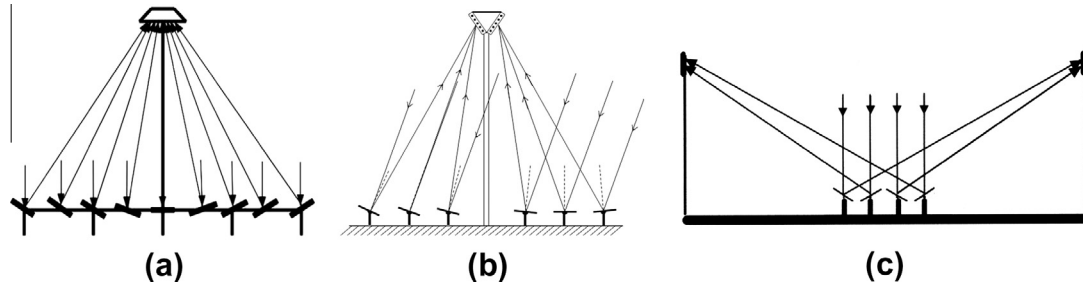


Fig. 6. Different receiver configurations: (a) one horizontal receiver in the middle of each array (from [55]), (b) two tilted receivers in the middle of each array (from [72]) and (c) receivers in both sides of each array (from [69]).

however, the inclination of the receivers could imply convection fluxes within such receivers increasing heat transfer to the window, and the view factor to the sky, and specifically to the horizon – that has a lower equivalent temperature – would increase. The three possible receiver configurations are depicted in Fig. 6.

In this paper, a horizontal receiver placed in the middle of the mirrors array is considered. Doing so, the view factor to the sky is minimized, and so are thermal losses due to radiation.

2.2. The solar field

Variation of the total thermal power impinging onto the receiver and its flux map along the day has traditionally been identified as a major handicap for LFR technology. This problem is first due to the optical efficiency of the solar field, which varies more than in trough collectors [67]; but it is also due to the change on total radiation falling within the field, caused by the zenith angle. In addition, low average concentration factors have been associated with LFR, around 15 suns [50,51,73]. It has been pointed out in the previous Section that different radiation qualities, i.e. thermal fluxes impinging onto the receiver, lead to different exergy efficiencies. However, concentration factors as low as 10 suns are enough to preheat the fluid up to 300 °C with an adequate performance.

Linear Fresnel reflectors are said to be made out of flat mirror strips focusing onto the same linear receiver, located over the array of mirrors. However, the reality is that mirrors are not always flat, even though they look like; a higher concentration factor may be achieved if mirrors are slightly bent to focus onto the receiver central point. The perfect focusing shape would be, as in trough collectors, a linear parabola. However, there are two important differences between trough and Fresnel collectors: first, in the former, the receiver moves with the reflective surface, always staying in the focus, while in the latter it is fixed, and so when the mirrors rotate to track the sun, their focus change, not being located anymore in the receiver position. Second, while trough aperture is large compared to the distance to the focus, the rim angle being over 100°, in Fresnel reflectors the mirrors aperture is normally well below 1 m, while the distance to the receiver may be as high as 20 m.

The second difference forces trough collectors to adopt a parabolic shape, as it is the only way to focus onto the receiver for such a large rim angle. The need to focus during all day, tracking the sun, resulted in the need of using movable receivers, which always stays at the actual focus line. This system has the advantage of approximately maintaining the concentration along the day, but implies many problems in the rotating joints or flexible hoses, where toxic leakages are common.

Similarly, Fresnel features also imply disadvantages and advantages: the receiver being fixed, when the sun is out of its reference position the mirrors do not focus exactly to the receiver centerline. For minimizing lateral drifts when the receiver is not in the mirror focus, it is advised to rotate the mirror around an axis which

belongs to the reflective surface. On the other hand, the mirrors aperture being relatively narrow, there is no need to use a parabolic shape. A cylindrical shape may be used instead [68], which would result in easier manufacturing and thus in lower prices. In addition, the curvature of the mirror being so small, the total use of reflective surface is reduced when compared to troughs.

As it has been said, LFR mirrors will only focus onto the receiver centerline for their reference position. Such reference may be the same for all mirrors, i.e. at a given time of the day all mirrors are perfectly focusing onto the receiver centerline, or specific for each mirror. If the design reference position chosen is when the sun is on its zenith, the maximum radiation will be maximized in the center of the mirror at noon, but it will be more dispersed during the morning and evening. On the other hand, if a specific reference may be taken, when the sun, the receiver and the mirror itself are in the same plane. Doing so, all mirrors are never perfectly focused at the same time, and thus the radiation map in the receiver may vary less along the day. However, the lateral drift of the reflected rays when mirrors are unfocused may be minimized if the rotating axis belongs to the mirror surface, as suggested by [74].

Other solar field variables apart from the mirror shape are the following:

- The mirror widths, W_i .
- The number of mirrors, n .
- The total width of mirrors, W_t .
- The receiver height, H .
- The solar field width, W_f .
- The solar field filling factor, FF .

Some of these variables are connected via the following formulae:

$$W_t = n \cdot W_i \quad (2)$$

$$FF = W_t / W_f \quad (3)$$

And therefore there are four independent variables that define the solar field: the filling factor, the number of mirrors, their width and the receiver height¹; the first three variables define the array of mirrors, while the last one fixes the focusing point. This statement admits that all mirrors are equidistant and are the same wide; obviously this is an arbitrary consideration that is required as first approximation to understand the basis of the design. Other authors have tackled the problem considering different filling factors and widths across the array for different purposes [66], but this would be too cumbersome for this study, as it would increase the number of variables by $2 \cdot n$.

¹ If the solar field were oriented in an East–West arrangement, the array should be asymmetrically placed respect to the receiver, and thus a fifth variable would be needed



Fig. 7. A picture of the Fresdemo prototype with the main geometrical characteristics.

2.3. Monte Carlo model characterization

Taking into account these considerations, a Ray Tracing model has been developed on Matlab, with the four variables previously defined – i.e. admitting the same width and lateral shift for all mirrors. This model is used to depict the features of radiation intensity in the receiver along different days of the year, assuming different mirror shapes. At each instant of the day 10,000 rays are spread within the field, assuming that their direction differs from the theoretical impinging rays by a pill-box error, due to the sun shape. The rays impinging onto the mirrors are reflected, assuming a Gaussian error in the reflective surface form due to manufacturing.

The model was dimensioned with the Fresdemo prototype, a LFR solar field installed in the Plataforma Solar de Almerfa by Solarmundo [48]. Such solar field consists of 25 mirrors 60 cm wide, with a distance of 85 cm between two consecutive mirror centerlines, and a 50 cm wide receiver placed 8 m above the central mirror (see Fig. 7). The actual receiver consists of a one-tube receiver with secondary reflector; however, the purpose of the study being the optical process, the receiver was modeled as flat and horizontal, with no discussion on whether it is a multitube or one-tube, and with or without secondary reflector.

The prototype is installed in Almerfa – Latitude $37^{\circ} 5'$ Longitude $-2^{\circ} 21'$ –, with North–South orientation. Regarding the optical parameters, the sunrays have been modeled as a distribution given by Buie et al. [75–77], which is close to pill-box with a cone semi-angle of 4.65 mrad. The mirrors surface is assumed to have Gaussian errors, the sigma considered being 2.5 mrad. Finally, the reflectivity of the mirrors is assumed to be 0.9.

3. Flux intensity across the receiver depending on the mirror shapes

Linear Fresnel reflectors are said to achieve very low average concentration factors. In this section the actual concentration factor across the receiver is studied for different days of the year. As stated in previous Section, four mirror shapes are modeled in this work: flat mirrors, cylindrical mirrors with specific reference, parabolic mirrors with specific reference, and parabolic mirrors with zenith reference.

If flat mirrors were used with the previously described configuration, we would find the radiation intensity shown in Fig. 8a. One may observe that the maximum concentration factor is very low, around 18 suns; in addition, after the general shape, one may deduce that an important part of the radiation is lost by the sides

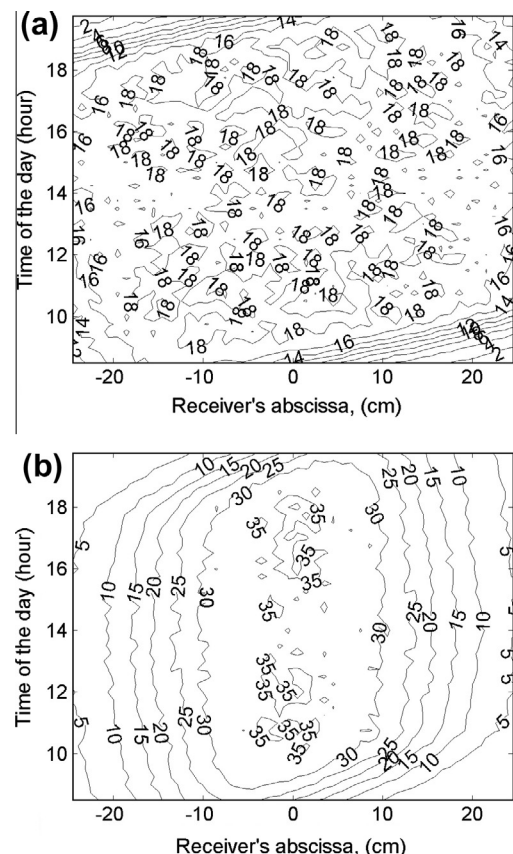


Fig. 8. Concentration factor variation across the Fresdemo receiver for (a) 25 flat mirrors 60 cm wide and (b) 50 flat mirrors 30 cm wide along the day 21st June, assuming Buie distribution for the sun, and a Gaussian error in the reflective surface slope with $\sigma = 2.5$ mrad.

of the receiver. This makes sense, as mirrors being flat, they do not imply an extra concentration, and they are wider than the receiver itself. If the number of mirrors were doubled, their width being only 30 cm (same total surface), the concentration features would be improved, achieving around 35 suns in the central strip of the receiver (see Fig. 8b).

However, it seems that the concentration performance of flat mirrors is not very good, far from trough collectors maximum concentration ratios (60–80 suns), and thus, bent mirrors should be studied. A model with the original Fresdemo configuration – 25 mirrors 60 cm wide – has been used for the three bent reflective shapes, which results in much higher concentrations for the same day – see Fig. 9.

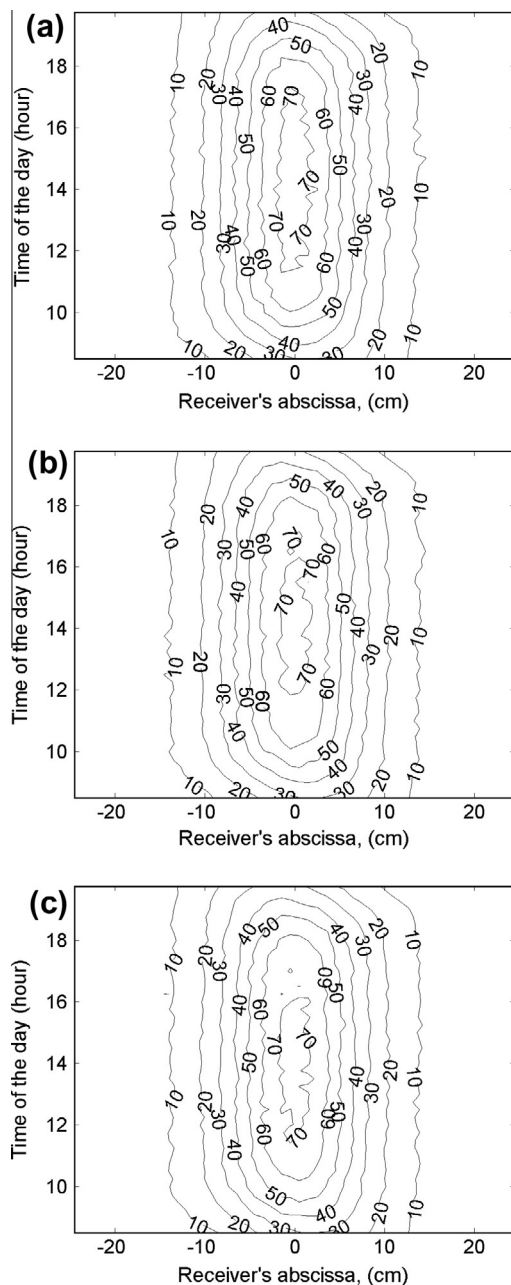


Fig. 9. Concentration factor (suns) variation across the Fresdemo receiver for (a) parabolic mirrors with zenith reference, (b) parabolic mirrors with specific reference and (c) cylindrical mirrors along the day 21st June, assuming Buie distribution for the sun, and a Gaussian error in the reflective surface slope with $\sigma = 2.5$ mrad.

The first result that can be deduced comparing Fig. 9b and c is that there is no actual difference in the concentration features between parabolic and cylindrical shapes if the same reference is used. This may be surprising at first glance, but actually is not if we take into consideration that the aperture of the mirrors is extremely low: an angle between 1° and 2° . From these results, it seems obvious that the designer should consider cylindrical shapes, easier to manufacture than parabolic mirrors.

On the other hand, comparing zenith and specific references one can conclude that even though maximum concentration factor is slightly higher for the former, which has a wider isoconcentration line of 70 suns, the global difference is negligible – see position of the contour line corresponding 20 suns. Therefore, one can conclude that the use of cylindrical mirrors with specific reference is advisable in LFR, with similar results to parabolic shapes, but much higher performance than that of flat reflectors.

The strip-like shape of the flux map may be regarded as a bad feature. However, this is very interesting when using a multitube receiver: doing so, the heat transfer fluid could be preheated in the lateral strips – it has been said in Section 2.1 that a radiation factor around 10 suns is enough to preheat the heat transfer fluid up to 300°C – with a final heat up to high temperatures in the central part of the receiver, which has concentrations as high as in trough collectors.

Nevertheless, maximum concentration factors diminish strongly during spring and winter. There are two reasons for this to happen: first, the sun being in a lower position, the distance traveled by the reflected ray increases, and so does the actual deviation due to the sun shape and reflection errors. But there is also a radiation diminution due to the longitudinal component of the impinging rays, which cannot be concentrated by linear concentrators, i.e. this issue affects the same to both linear Fresnel reflectors and parabolic troughs. It is worth to point out that the concentration values given in this work refer to the plane normal to the impinging radiation, not to the radiation measured in the horizontal plane. The latter reason for lower concentrations may be observed in Fig. 10a, where it is shown that the effect is negligible in June, while in December only around 50% of the impinging radiation does not have a longitudinal component.

From this Figure one can deduce that, if a concentration factor of 70 suns is assumed in summer for trough collectors with North–South orientation, the concentration in spring would be around 56 suns, while in winter this value would decrease down to 35 suns, even if no dispersion effect due to the longer distance traveled by the reflected ray is considered.

In addition to this, linear Fresnel reflectors are quite sensitive to the increase of the distance traveled by the light after reflection. Such distance is responsible of the rays deviation that limit the average concentration, even when the sun impinges with no longitudinal component. One can observe in Fig. 10b that the path followed by the reflected ray increases importantly in December, doubling the distance traveled if the longitudinal component were zero.

The effect caused by both issues is depicted in Fig. 11, that represents the concentration factor evolution across the receiver along the 21st March and 21st December, assuming cylindrical shaped mirrors.

Fig. 11a shows that the concentration achieved during March in the central 10 cm of the receiver is slightly lower than what could be expected in trough collectors. In addition, it is observed that the performance in the lateral strips is not being very different to that achieved during June for the same LFR, as isoconcentrations around 20 suns are placed in the same position (10 cm from the centerline). However, the concentration achieved during winter is well below the previous values, with maximum concentrations around 25 suns. This would imply a lower efficiency in transfer heat to the HTF, although 400°C could be achieved [68].

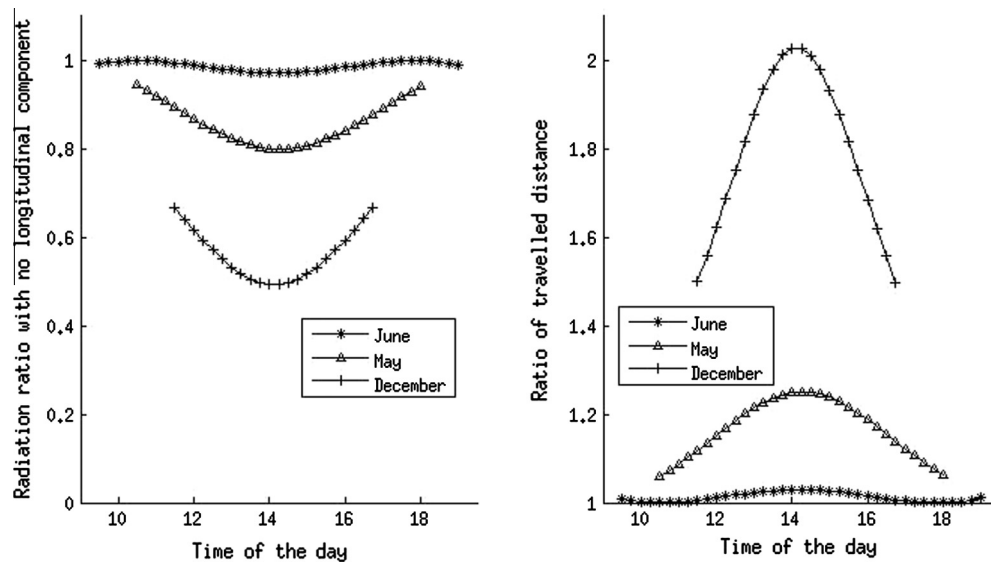


Fig. 10. (a) Ratio of impinging radiation with no longitudinal component (which can be concentrated by linear collectors) and (b) ratio of traveled distance increase due to such component in Almerfa along the 21st June, May and December.

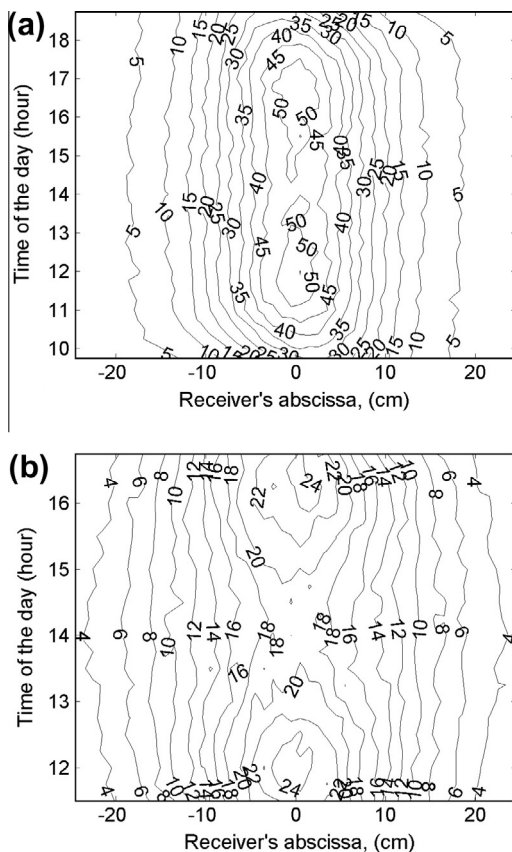


Fig. 11. Concentration factor (suns) variation across the Fresdemo receiver assuming 25 cylindrical mirrors along the day (a) 21st March and (b) 21st December, assuming Buie distribution for the sun, and a Gaussian error in the reflective surface slope with $\sigma = 2.5$ mrad

It is also remarkable that whereas in summer and spring the maximum concentration is achieved by midday, in winter it is achieved during the morning and evening. There are actually two opposite effects, which place the maximum concentration at a given time of the day: on the one hand, one can observe in Fig. 10

that at midday the longitudinal component of the impinging radiation gets its maximum value; on the other hand, at this time all mirrors are close to their reference position, and thus the geometrical efficiency to concentrate radiation is higher. When the former fact does not imply important losses, as it is the case during summer, maximum concentrations are achieved at midday. On the opposite, in winter this effect becomes more important, which displace the maximum concentration in the morning and afternoon.

It is worth pointing out that the longitudinal component of the impinging radiation is proportional to the sinus of the zenith angle, and its effect depends of its square power. Therefore, from a given zenith angle the effects of such longitudinal component become very important. As a example, the average longitudinal component difference between June and May is larger than that between May and December; however, May's concentration flux map is closer to June's than to December's.

Nevertheless, results shown in this Section imply that concentration factors achieved with linear Fresnel reflectors are importantly higher than the values previously thought.

4. Flow variation along the day

In Section 3 it has been observed that LFR may achieve higher concentrations than trough collectors, even though the variation along the year is somehow higher than in the other linear technology. In some scientific and pedagogic literature one can find that another said drawback of LFR is that the concentration is supposed to vary importantly along the day. This section intends to show that this is only true for some designs.

It is said that one advantage of LFR is that mirrors may be placed very close together, thus increasing the filling factor. At the upper limit, they could be installed with no gap between one mirror and its neighbor. If such solar field is installed, we can assume that all the solar radiation impinging onto the solar field may be collected at any time, if blocking effects and other losses are disregarded. Therefore, the total power collected along the day would follow a cosine shape, as depicted in Fig. 12, which implies important variations along the day.

However, if the filling factor approaches 100%, shadows during the morning and evening will be very important, thus reducing the economical benefit of the material installed. Therefore, it seems

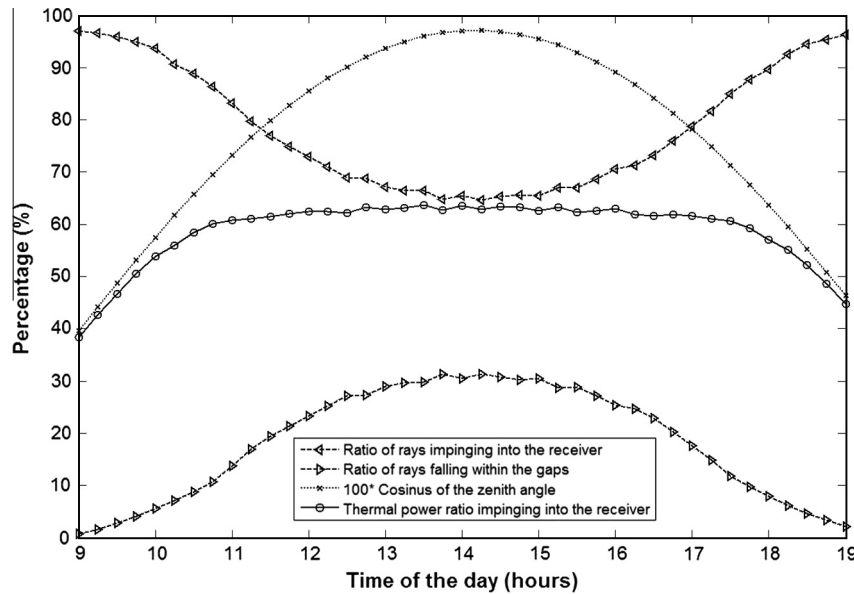


Fig. 12. Optical efficiency, ratio of gaps falling within gaps, cosine effect and thermal power ratio impinging onto the receiver for circular mirrors along the day 21st June [68].

logical to install the mirrors slightly sparse, so that shadowing effects are limited. If we use the Fresdemo configuration, with a filling factor of 71%, it results that during the morning the power collected increases as shadows diminish. Nevertheless, around 10 am the thermal power collected stops increasing, see Fig. 12, as there are no more shadows, and the extra power impinging onto the solar field falls in the gaps.

On the one hand, one could say that the optical efficiency, seen as the ratio number of rays impinging onto the receiver to number of rays impinging onto the solar field, diminishes during the day, as the gap losses increase. But the use of mirrors would be maximized, thanks to shadowing reduction. In addition, optical efficiency should not be seen as a key variable when it takes into account gap losses, as land cost is negligible compared to materials and engineering costs.

From these results, one can deduce that the power input during the day may be maintained approximately constant, as would happen in a trough collector.

5. Conclusions and future work: a way to reduce costs via a competitive design

Linear Fresnel reflectors appear as a technology with very high potential to reduce costs. They do not suffer from the mentioned trough disadvantages such as oil leakages, receiver failures and heavy structures, thanks to a fixed receiver and smaller slightly bent mirrors. In addition, they have the advantages of linear collectors. However, there is a general belief that LFR achieve very low concentration factors, and that such concentration varies along the day importantly. This has made companies to prefer to invest in well known technologies to minimize risks.

At current time we have powerful tools that enable us to predict the potential of different technologies, and to determine whether the industry is advancing in the right learning curve, or if the cost reduction by such curve is limited. This work presents the results from a Monte Carlo model, depicting the concentration map in the receiver along the day, for different mirror shapes and different days of the year.

From these results one can deduce that concentration factors achieved with the Fresdemo configuration are much higher than suspected at first glance, as high as in trough collectors at the receiver centerline. In addition, it seems that a good optical design, with well chosen filling factor, drives to approximately constant radiation flux map during many hours per day. On the other hand, the longitudinal component of the impinging radiation may imply higher effects in Fresnel fields than in troughs. As a result, there are important concentration differences between summer and winter days.

If an East–West orientation is assumed, differences between summer and winter will diminish. Therefore future work should aim at the study of such orientation. In addition, the design variables may be changed to optimize the performance of the solar field, which will be soon investigated.

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